SEM STUDY OF DEFORMATION AND FAILURE MECHANISMS IN STRAINED ELASTOMERS

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ABSTRACT

In this study, the deformation and damage mechanisms on meso and macro scales in a particulate composite and a polyurethane material, Solithane 113, were investigated. The particulate composite contains 87% by weight of hard particles embedded in a rubbery matrix. Experimental data were analyzed and the effect of material's microstructure on the deformation and failure mechanisms are discussed.

INTRODUCTION

Polymeric materials provide many excellent properties such as light weight, ease of processing and corrosion resistance by comparison with traditional metallic materials. In many applications, particulate fillers are added to polymeric materials to improve various properties of plastics, such as to increase surface hardness, reduce shrinkage and eliminate crazing after molding, improve fire retardancy, modify the thermal and electrical conductivities, and improve strength and abrasion resistance while maintaining extensibility. Highly filled particulate composites are now increasingly being used in civil structures for load bearing application, such as bridge decks and highway pavement. In the automotive industry, carbon black filled rubbers are used in tires. In the rocket industry, solid propellants, containing hard particles embedded in rubbery matrixes, are used as solid fuels. Failure in all these materials is heavily dependent upon the interaction between the particles and the matrix, especially on the debonding of particles and matrix.

It is well known that, on the microscopic scale, polymeric materials may be considered inhomogeneous materials. When these materials are stretched, the different crosslinking densities of polymeric chains can produce highly inhomogeneous local stress and strength fields. Similarly, on the

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microscopic scale, a highly particle filled elastomer, such as a solid propellant, is an inhomogeneous material. Depending on the magnitude of the local stress and the local strength, damage can be developed in these materials (1-4). The damage process is time dependent and is the main factor responsible for the time sensitivity of strength degradation as well as the fracture behavior of the material. Therefore, in order to gain an advanced understanding of the failure process in these materials, a detailed knowledge of deformation process as well as damage initiation and evolution mechanisms are required.

In this study, the deformation and failure mechanisms on the meso and macro scales in Solithane 113 and a particulate composite, containing 87% by weight of hard particles embedded in a rubbery matrix, were determined using a Scanning Electron Microscope (SEM). Experimental data were analyzed to determine the effect of material's microstructure on the deformation and failure mechanisms in the materials. In the following paragraphs, we will discuss the damage and fracture mechanisms on the macro and meso scales in the particulate composite and in the Solithane 113.

RESULTS AND DISCUSSION

It is well known that the measured material strengths of most materials are found to be much smaller than their theoretical cohesive strengths. The discrepancy in strength values is believed to be due to the presence of defects or inherent flaws in the materials. These defects and damage may be produced in the manufacturing process or in service. For highly filled polymeric materials, the defects or damage occur in the form of microcracks or microvoids in the matrix or as debonding between the matrix and the filled particles. Voids usually nucleate and grow near the particles, especially when the material is subject to a triaxial stress state. If the voids are closely spaced, the voids may coalesce to form cracks. When voids or cracks are formed, the material is damaged, and the modulus as well as strength degrades. In addition, local failure, either cohesive in the binder or adhesive at the interface, occurs where the local binder rupture strength or the interfacial bond strength is lowest.

When crack occurs, the high stress at the crack tip will induce high damage near the crack tip region. The high damage zone at the crack tip is defined as the failure process zone, which is a key parameter in viscoelastic fracture mechanics (5-6). Experimental data reveal that when the local strain reaches a critical value, small voids are generated in the failure process zone. Due to the random nature of the microstructure, the first void is not necessarily formed in the immediate neighborhood of the crack tip. The formation of the voids is not restricted to the surface of the specimen where the maximum normal strain occurs. Since the tendency of the filler particle to separate from the binder under a triaxial loading condition is high, it is expected that voids or damage zones will be generated in the specimen's interior. Consequently, there are a large number of strands essentially made of the binder material, which separate the voids, that form inside the failure process zone. These damage processes are time-dependent and are the main factor responsible for the time-sensitivity of strength degradation as well as fracture behavior of the material.

Figure 1 is typical set of photographs showing the crack profile during opening and growth of a crack in the composite material specimen. Figure 1 shows that crack tip blunting occurs both before and after crack growth. Due to the heterogeneous nature of the composite material, the degree of blunting varies with the position of the advancing crack tip. This suggests that the local microstructure near the crack tip plays a significant role in the blunting phenomenon.

During the blunting stage, voids develop in the failure process zone. The failure of the material between the void and the crack tip causes the crack to grow a short distance. In other words, the coalescence of the void and the crack tip lets the crack grow into the failure process zone. This kind of crack growth mechanism continues until the main crack tip reaches the failure process zone tip. When this occurs, the crack tip resharpens temporarily. Thus, the process consists of a blunt-growth-blunt phenomenon which is highly nonlinear. Referring back to Fig.1, a close look at the crack tip region reveals that the failure process zone has a cusp shape which is consistent with that predicted by Schapery (6) in his study of fracture of viscoelastic material. In the failure process zone, the material can be highly nonlinear and suffer extensive damage, which will be discussed later.

Experimental data indicate that the direction of the failure process zone with respect to the crack plane varies from specimen to specimen. This is believed to be related to the size of the highly strained region as well as the local microstructure of the material in that region. For a large magnitude of tip blunting, the size of the highly strained region is also large. Therefore, depending on the local microstructure, the direction of the failure process zone shows a relatively large variation. Experimental results reveal that before crack growth, the failure process zone develops either above, below, or along the crack plane. After crack growth, the successively developed failure zones at the tip of the propagation crack undulate about the crack plane, resulting in a zig-zag shape of crack growth. It is interesting and important to note that the crack has a tendency to grow in the average direction perpendicular to the applied load direction. The change of the stress concentration location as the result of crack tip blunting also contributes to the variation in failure process zone direction. When the crack tip is extensively blunted, the stress concentration location changes from the tip of the sharp crack to the upper and lower corners of the blunted crack. Therefore, the probability of developing a failure process zone near the corners of the blunted crack is greater.

As mentioned earlier, the development of damage at the crack tip will redistribute the stress in the immediate neighborhood of the damaged area, resulting in an increase in stress in the material outside the damage zone. Consequently, the material outside the damage zone will also accumulate damage. The damage intensity in the newly developed damage zone depends on the magnitude of the applied load, which is a function of time. When the material inside the old failure process zone fails, a new failure process zone has formed at the tip of the retargeted crack. Experimental evidence reveals that the time required for the formation of the failure process zone decreases as the applied load is increased. These local damage and fracture processes are time-dependent and are the main factor responsible for the time-dependent discontinuous crack growth in the material.

Figure 2 shows the deformation and damage mechanisms on the meso-scale inside the failure process zone. It is seen that voids and ligaments are formed in the failure process zone. The basic damage mechanisms consist of void formation and coalescence. The failure of the ligament at the crack tip leads the crack to grow into the failure process zone. It is interesting to point out that, due to the inhomogeneous nature of the microstructure, similar damage zones are formed at other locations inside the failure process zone. By comparing Fig.1 with Fig. 2, it is clearly indicated that the basic deformation and damage mechanisms on the meso-scale and macro-scale in the particulate composite are similar.

Having discussed the deformation and damage mechanisms in the particulate composite, we will proceed to discuss the failure and damage mechanisms in Solithane 113.

Figure 3 shows the side view of the specimen containing a crack, which was cut with a razor blade. Due to the difficulty in cutting the small crack in a small specimen made of a soft material, the initial crack is not perpendicular to the edge of the specimen. In other words, the initial crack has an angle with respect to the loading direction. Under this condition, the crack tip stress field consists of normal and shear stresses, or the crack tip is subjected to a Mixed-Mode loading condition. When the local stresses reach the critical values the crack starts growing. During the early growing stage, the crack turns under mix-mode loading condition. After it grows a short distance, the turning process completes, and it propagates perpendicular to the loading direction; it implies that the crack grows under pure normal loading condition, or Mode I condition. Due to low magnification 40X, the failure process zone at the crack tip is too small to be observed. In order to see the deformation and damage mechanisms at the crack tip, the magnifications are increased to 500X and 1000X as shown in Fig. 4. According to Fig. 4, we see that ligaments with widths varying from 1 micron to 10 micron are formed at the crack tip region. The failure process zone length is about 50 micron. The crack growth mechanism consists of the coalescence of the void with the crack tip as a result of the breakage of the ligament between the void and the crack tip; which is similar to the crack growth mechanism observed in the particulate composite. In addition to showing the side view of the crack, the top views of the crack at 150X and 250X magnifications are shown in Fig. 5. The formation of voids and ligaments at the crack tip are clearly indicated.

CONCLUSIONS

In this study, the deformation and damage mechanisms in a particulate composite and a polymeric material, Solithane 113, were investigated. For the two materials investigated, the development of voids in the material is the basic damage mechanism and a highly damaged region, or failure process zone, develops at the crack tip. The lengths of the failure process zone are about 1 mm. and 0.05 mm. for the particulate composite and Solithane 113, respectively. The basic crack growth mechanism consists of the coalescence of voids with the crack tip.

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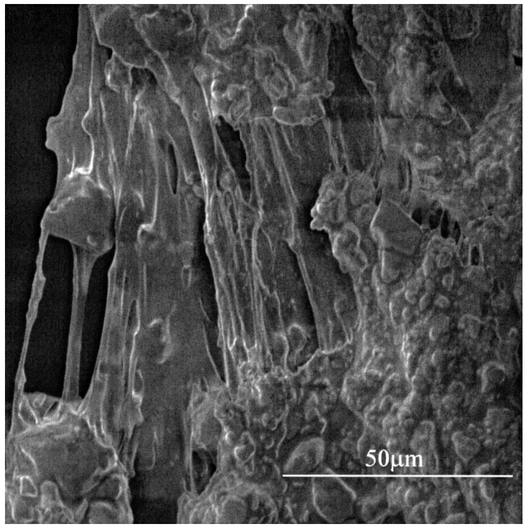

Figure 2. Local damage at crack tip.